

Explosions Triggered by Violent Binary-Star Collisions: Application to Eta Carinae and other Eruptive Transients

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ABSTRACT

This paper discusses a model where a violent periastron collision of stars in an eccentric binary system induces an eruption or explosion seen as a brief transient source, attributed to luminous blue variables (LBVs), supernova (SN) impostors, or other transients. The key ingredient is that an evolved primary increases its photospheric radius on relatively short (year to decade) timescales, to a point where the radius is comparable to *or larger than* the periastron separation in an eccentric binary. In such a configuration, a violent and sudden collision would ensue, possibly leading to substantial mass ejection instead of a binary merger. Repeated periastral grazings in an eccentric system could quickly escalate to a catastrophic encounter. Outbursts triggered by tidal disturbances or powered by secondary accretion of the primary star’s wind have been suggested previously. Instead, this paper proposes a much more violent encounter where the companion star plunges deep inside the photosphere of a bloated primary during periastron, as a result of the primary star increasing its own radius. This is motivated by the case of η Carinae, where such a collision must have occurred if conventional estimates of the present-day orbit are correct, and where peaks in the light curve coincide with times of periastron. Stellar collisions may explain *brief* recurring LBV outbursts like SN 2000ch and SN 2009ip, and perhaps outbursts from intermediate-mass progenitor stars (i.e., collisions are not necessarily the exclusive domain of very luminous stars), but they cannot explain all non-SN transients. Finally, mass ejections induced repeatedly at periastron cause orbital evolution; this may explain the origin of eccentric Wolf-Rayet binaries such as WR 140.

Key words: binaries: general — stars: individual (Eta Carinae) — stars: massive — stars: mass loss — stars: variables: other

1 INTRODUCTION

Considerable mystery surrounds the class of transients that includes giant eruptions of luminous blue variables (LBVs) and other so-called supernova (SN) impostors. These are thought to be non-terminal eruptions of massive stars, although recent evidence suggests that similar eruptions occur in evolved intermediate-mass stars (initial masses $\lesssim 8 M_{\odot}$) as well. These eruptions have a diverse range of peak absolute magnitude, fading rate, total energy, spectral morphology, and progenitor initial masses (see Smith et al. 2010b for a recent discussion of members of the class). So far, there is no plausible theory to explain these outbursts.

Included among these non-SN outbursts are very brief events, which reach peak absolute magnitudes of -12 to -14 , but which only last a few days or weeks, in contrast

to other LBV eruptions that can go on for years. Some of these brief events seem to repeat: Multiple ~ 100 day events were seen before the eruption of η Car (Smith & Frew 2010), numerous rapid spikes were seen before the eruption of SN 1954J (Tammann & Sandage 1968), and in modern times both SN 2000ch and SN 2009ip have shown recurring rapid brightening and fading (Wagner et al. 2004; Pastorello et al. 2010; Smith et al. 2010a; Drake et al. 2010). The repetition of events is obviously suggestive of binary encounters, but this is quite speculative for extragalactic eruptions where we have limited information about the progenitor systems.

However, η Carinae is a unique nearby case, known to have survived to the present day in a binary system with reasonable estimates of the orbital parameters. We know the approximate amount of mass ejected in the eruption by measuring its circumstellar nebular mass, and fortunately,

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we have a good historical record of the observed brightness during the event as well.

Recently, Smith & Frew (2010) presented over 50 newly recovered historical estimates of the visual magnitude near the peak of the mid-19th century eruption. They demonstrated clearly that the Great Eruption was not a simple 15–20 yr brightening of the star as is often assumed. Instead, there were multiple brief 100-day peaks leading up to the eruption. Smith & Frew (2010) showed that these brief peaks occurred within weeks of periastron, providing that the orbital period was slightly smaller at that time than the period measured today; this should be the case, since the system ejected $15 M_{\odot}$ during the event (Smith et al. 2003).

It is hard to believe that major brightenings occurring repeatedly so close to times of periastron would be a coincidence. This begs the question: “What actually happened during the periastron encounters of Eta Carinae in the early 1800s?” In §2 we consider the parameters of η Carinae, and show that a stellar collision must have occurred at periastron before and during the Great Eruption, where the presumably main-sequence O-type secondary star plunged deep inside the effective photosphere of the bloated primary. This is certainly a violent and exotic encounter, spurring several other questions that we attempt to address briefly: What are the physical and observable effects of one star plunging into another’s envelope and emerging? What is the energy budget in such an event? What causes the primary star’s radius to increase so quickly, and what other types of systems might experience this? If the system failed to merge and has survived as a binary today, then how does such an encounter affect its orbital evolution? We hope that ideas outlined here will help guide numerical models of such an encounter. In a subsequent paper, we will discuss possible implications for the structure of η Car’s nebula.

2 ETA CARINAE

In the conventional picture of LBV outbursts of the normal S Doradus-type, a star will brighten at visual wavelengths by an amount comparable to its bolometric correction (BC), as it transitions from a hot quiescent state (usually very late O-type or early B-type) to its cool state as an F-type supergiant with an apparent temperature around 7000–8000 K. While this does not appear to hold for all giant LBV-like eruptions (Smith et al. 2010b), this paradigm seems well established for conventional S Doradus-type excursions of LBVs (Humphreys & Davidson 1994).

By transitioning to cool temperatures at roughly the same luminosity, an LBV must increase its emitting radius by a huge factor, $R \propto T^{-2}$. For a typical transition from early B to an F-type supergiant, the radius may increase by a factor 7–10. Whether this is a true increase in the star’s hydrostatic radius (Groh et al. 2009) or the radius of a pseudo-photosphere in the opaque wind (Davidson 1987) is controversial. The important point, though, is that any release of energy occurring inside the optically thick (pseudo)photosphere will be thermalized.

This *large and sudden increase in radius* is the most crucial physical change in the system, for the model discussed in this paper. In an LBV that is a single star or a very wide binary, this S Doradus excursion will simply cause the star

to brighten at visual wavelengths, on typical timescales of years to decades as seen in the standard Hubble-Sandage variables (Hubble & Sandage 1953; Humphreys & Davidson 1994). However, if the LBV happens to reside in a binary system with a period of a few years and with some eccentricity, the huge increase in radius can be cataclysmic.

Consider what happens if we apply this entirely conventional picture of S Doradus variability to η Carinae. In the century before the Great Eruption, η Car steadily brightened from an apparent visual magnitude of about 3.5 to 1.2 mag (Frew 2004; Smith & Frew 2010).¹ The simplest interpretation of this ~ 2.3 mag brightening is a long S Dor-type excursion where the star remained at constant luminosity, but brightened at visual wavelengths by an amount equal to its BC. A BC of 2.3 mag corresponds to a temperature of around 20,000 K, or an approximate spectral type of B1 Ia. This is roughly consistent with the star’s present-day state (e.g., Hillier et al. 2001). The current bolometric luminosity of η Car is about $4 \times 10^6 L_{\odot}$ (Smith et al. 2003), allowing for a 10–20% contribution to the total luminosity from a companion star. At constant L , its photospheric radius must then have increased from $\sim 170 R_{\odot}$ (0.8 AU) to about $1400 R_{\odot}$ (6.6 AU).

In the present-day orbit, models for the X-ray colliding wind emission and other data suggest the following orbital parameters: $e=0.9$, $P=5.54$ yr, $a=15.9$ AU, $M_1=100 M_{\odot}$, and $M_2=30 M_{\odot}$ (Parkin et al. 2009; Okazaki et al. 2009; Pittard & Corcoran 2002; Corcoran 2005; Mehner et al. 2010). The closest periastron separation between the two stars in this orbit is only 1.6 AU. Figure 1 illustrates the obvious problem here. By the time η Car brightened to its observed early 19th century magnitude, its characteristic emitting radius was substantially larger than the periastron separation in the binary system we see today. In other words, *the secondary star would have plunged deep inside the photosphere of the primary star at periastron*. We do not know the pre-1844 eccentricity, but Figure 1 shows that a violent collision would still occur even for a hypothetical eccentricity as low as ~ 0.7 (dashed ellipse). This is a rather exotic state of affairs, with implications discussed below.

Smith & Frew (2010) have demonstrated that the brief brightenings of η Car in 1838 and 1843 occurred within weeks of periastron, if the pre-1844 orbit is $\sim 5\%$ shorter than that observed today due to mass loss from the system. The indication of Figure 1 is that this is no mere tidal interaction of two close stars, but a brutal collision where one star burrowed deep inside the other star’s bloated envelope. The duration of the periastron collision itself is the time for the secondary to move from point p to q in Figure 1, which in this case is a few months. This is, interestingly, comparable to the duration of the X-ray outbursts seen in the present-day colliding-wind binary. It is also comparable to the ~ 100 day duration of the brief brightening events in 1838 and 1843 (Smith & Frew 2010). Based on this, we hypothesize that the brief 1838 and 1843 brightening events, where η Car’s bolometric luminosity increased for a short

¹ Note that putative fluctuations between 2nd and 4th mag are from upper and lower limits. Reliable reports of η Car’s magnitude are consistent with a steady brightening during the 18th century (see Smith & Frew 2010).

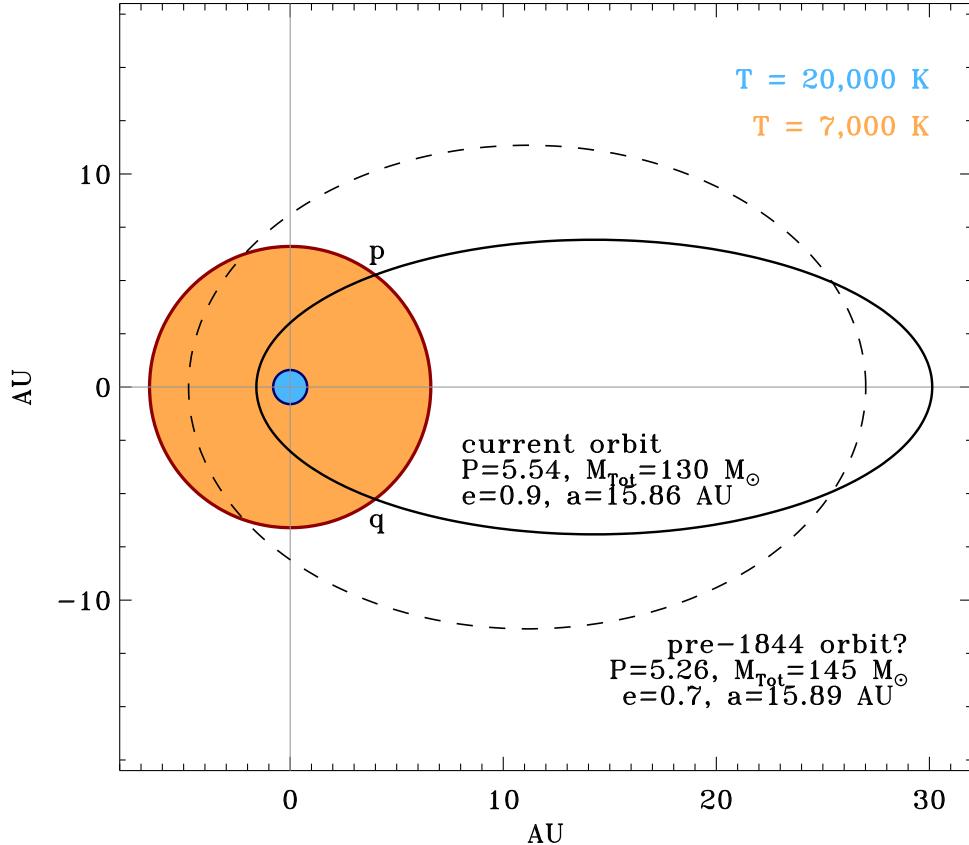


Figure 1. A sketch of the η Carinae binary system. The solid ellipse uses conventional parameters for the present-day orbit derived from model fits to the X-ray light curve (i.e., $e=0.9$, although some models have proposed even higher eccentricity). The dashed ellipse is a hypothetical orbit before the major mass ejection of the Great Eruption when $\sim 15 M_{\odot}$ was lost from the system; we do not know the pre-1844 eccentricity, so we show a hypothetical lower value of $e=0.7$ for illustrative purposes. The smaller blue circle shows the effective photospheric radius of the primary in its present-day (and presumably its pre-1600 A.D.) state with $T_{\text{eff}} \simeq 20,000$ K and $L \simeq 4 \times 10^6 L_{\odot}$. The larger orange circle is the primary star's radius for the same luminosity and $T_{\text{eff}} \simeq 7,000$ K. Clearly, a violent collision would have occurred, placing the secondary well inside the primary star's photosphere.

time, were the direct observed result of this collision. The energetics of such an encounter are discussed next.

3 THE ENERGY BUDGET

What actually happens energetically when one star suddenly plunges deep inside the other's envelope? Real models for such an encounter do not yet exist. A conventional assumption in models is that when stars are in a close binary, the orbits will become tidally locked and circularize, leading to either mass-transfer or a merger in a thermal timescale. The case of η Car is quite different because the primary star's radius increased dramatically on a timescale of a few orbits, and the orbit is very eccentric, so circularization would not occur. Clearly the system survived the encounter and did not merge into a single star, because we see an eccentric binary today, and the times of periastron coincide with brightening events during the Great Eruption. Instead, the high orbital velocity at such a close periastron separation evidently permitted the secondary star to plow through the primary's envelope and escape out the other side.

Let us now consider the energy budget during such a collision. We take the duration of the collision to be ~ 100 days, as noted above. During the brief 1838 and 1843 events, η Car brightened by about 1.6 mag, and therefore radiated an extra $\sim 5 \times 10^{47}$ erg beyond what the star would have radiated anyway at its quiescent luminosity. If we attribute the ejection of the Homunculus nebula to these periastron collisions, which is not necessarily the case, then the energy budget climbs to $\sim 10^{50}$ erg because of the kinetic energy involved (Smith et al. 2003). We can evaluate a few hypothetical sources of energy in such an encounter:

Kinetic heating of the envelope. When one star plunges into another's envelope, friction will drain the kinetic orbital energy of the intruder and this will heat the envelope. The available energy is necessarily some small fraction of the total orbital potential energy (about 7×10^{48} erg in this case), since there were multiple encounters and the system did not merge. The radiated energy was about 10% of the available orbital energy, so frictional heating of the primary star's envelope is at least a plausible explanation for the increase in luminosity during the brief 1838 and 1843 events. It cannot, however, explain the radiated energy budget of

the entire eruption or the kinetic energy of the ejecta, so some other source must have powered the radiation of the main eruption and launched the Homunculus.

Radiation emitted by the secondary star. The secondary star itself is less luminous than the primary, so its own radiation trapped inside the primary star's envelope offers no relevant contribution to the energy budget. However, there is another consideration, mentioned next.

Accretion of primary star's envelope onto companion star. In a series of papers, Soker (see Kashi & Soker 2010, and references therein) has advocated a rather complicated model where a secondary star accretes material from the wind of the erupting primary at periastron. In this picture, the direct accretion luminosity of the secondary powers the extra radiation (for the full 15 yr duration of the Great Eruption), and bipolar jets associated with the accretion disk form the Homunculus nebula. The model is analytic and involves many unverified assumptions and assertions, and adopts huge primary mass-loss rates as a precondition. It is nevertheless worth considering, but the situation must be quite different from that envisioned by Soker et al. in several key respects: (1) instead of accretion from the primary star's wind, the secondary would be *inside the primary* and would accrete directly from the primary star's envelope (this affects the calculated Bondi-Hoyle accretion rate, since the envelope is probably static, and not an accelerated wind). (2) Any radiation of the accretion luminosity from the secondary would occur inside the photosphere of the primary, and would therefore be absorbed and reprocessed by it. Thus, the radiation we observe cannot be direct radiation from the accreting companion. (3) The observed periastron event was observed to last only \sim 100 days, so the accreted mass, total radiated energy from accretion, and time over which accretion operated must have been much smaller than calculated by Soker, who assumes that it occurs over \sim 10 yr and powers the full radiation of the Great Eruption. With much less mass accreted, the effect on the orbital evolution is less severe, and the mass accretion budget becomes more reasonable. (4) Hypothetical jets launched by the accretion disk around the secondary would need to drill through the primary star's envelope, so it is not clear that the jets would survive. Instead, they might simply impart their energy to the primary star's envelope and induce a sudden (bipolar?) explosion. This is of course very speculative, but the point is that the situation is quite different from an undisturbed accretion disk around a secondary star that blows collimated jets.

Induced mixing of fresh fuel into deeper layers. Dessart et al. (2009) has explored the possibility of explaining observed properties of some LBV-like transients with the deep and sudden deposition of energy that induces an explosion. One hypothetical source for this is the sudden nuclear combustion of only $0.01\text{--}0.1 M_{\odot}$ of fresh fuel mixed down into a deeper burning layer in the star. Massive stars may become unstable enough to do this on their own at convective boundaries (see Meakin & Arnett 2007), but if a $30 M_{\odot}$ star plunges deep inside the envelope of a $100 M_{\odot}$ star that is near the Eddington limit anyway, one might wonder if the ensuing disturbance could also trigger the necessary small amount of mixing. The density gradient at a convective core boundary is a formidable obstacle, but exploring the consequences of such an event may be interesting.

Although it may verge on overspeculation, this last mechanism has some advantages over the accretion model. Since the accretion onto the secondary can only cause the ejection of material in the outer envelope at a point where the binding energy is low, it is difficult to see how it could lead to the ejection of more than $10 M_{\odot}$ and 10^{50} ergs, as required for the formation of the Homunculus. Instead, deposition of energy at a depth corresponding to a binding energy of 10^{50} erg and where a larger mass reservoir is available seems like a more natural explanation (Dessart et al. 2009), which can potentially be achieved in an explosive burning scenario. Although models for triggering such an event have not yet been explored, these leading comments are perhaps justified, given the violent and exotic nature of such an encounter, plus the well-established observational basis that it did in fact occur in η Carinae.

4 THE PRIMARY STAR'S RADIUS, AND APPLICATION TO OTHER TRANSIENTS

Observationally, η Car's photospheric radius clearly increased in the two centuries leading up to 1844 (see Smith & Frew 2010). In such a very luminous and unstable system, one can plausibly attribute this to the inherent instability of a star flirting with the classical Eddington limit, as conventionally discussed for LBVs. In fact, the pre-1840s secular brightening could be attributed to a slow but otherwise normal S Doradus excursion, causing a change in the BC as discussed above. One might therefore expect other LBVs to be readily able to experience violent periastron collisions, if they happen to be in eccentric binaries. Observations of the solar neighborhood suggest that \sim 10% or more of binary systems have high initial eccentricity above $e=0.4$ (e.g., Mayor & Mermilliod 1984), although this distribution is not well known for massive stars. (The initial eccentricity distribution is needed to estimate the expected rates of periastron collisions.)

In that case, we may have a potential explanation for the very brief and repeated brightening events seen in SN 2009ip and SN 2000ch (Smith et al. 2010a; Pastorello et al. 2010; Drake et al. 2010). Both systems showed a rapid brightening and fading on time scales of several days – much quicker than one normally attributes to eruptions of LBVs. These brief episodes could plausibly be explained as periastral grazings or true collisions due to the primary star's increasing radius during S Dor excursions. The LBV instability is notoriously irregular, occurring on year to decade timescales. Depending on the orbital separation, periastron collisions may only occur when the star increases its radius to the maximum brightness in an S Dor event. Therefore, the appearance of sudden brightenings in a system which did not previously exhibit it — or in fact, the irregular disappearance and reappearance of brief eruptions — can be explained for LBVs in eccentric binaries. In other words, one can expect periodic repetition of periastron grazings and collisions, but *only when the primary is in an outburst state with an expanded radius*. The repeated eruptions may therefore not be strictly periodic because in some cycles, nothing observable will happen at periastron. Even so, an orbital period of around 190 days would provide satisfactory coincidences in the case of SN 2000ch, judging by the light curve from

Pastorello et al. (2010). As discussed in the next section, the first appearance of such behavior may be brought on by a runaway instability, leading to catastrophic encounters and subsequent mass ejections. When enough mass is lost, the envelope will contract again, thereby shutting off the repeated collisions.

Other stars besides LBVs will increase their photospheric radius during their evolution, although the typical few-year timescale for S Doradus variations of LBVs is well-suited to a sudden change in radius during an orbit. Imagine, for example, a star with an initial mass of $\sim 7 M_{\odot}$, born in an eccentric binary with a period of a few years. As a star works its way up the final asymptotic giant branch (AGB), one could imagine sudden encounters if times of periastron coincided with a major pulsation, for example. If these happen rather suddenly in an eccentric system, it may lead to a collision and mass ejections rather than mass transfer or merger. Perhaps this is an explanation for the LBV-like transients that seem to arise from relatively low-mass progenitors, like M85-OT, SN 2010U, V838 Mon, etc., which bear many similarities to the eruptions of known LBVs (see extensive discussion in Smith et al. 2010b, and references therein). Collisions and eruptions might also occur in the years immediately preceding a core-collapse SN, if the final burning phases trigger a rather sudden increase in the progenitor's radius, the implications of which are potentially important for understanding SNe IIn and Ib.

The observed case of η Car demonstrates that such a stellar collision will not necessarily lead to the successful merger of the pair of stars. Stellar mergers have already been suggested as potential explanations for objects like M85-OT and V838 Mon (e.g., Kulkarni et al. 2007; Tyenda 2005), but the non-merger collisions proposed here might be another viable explanation. Indeed a merger may occur in some cases, but the collision may instead trigger severe explosive mass ejection, which may leave the binary system less bound, and may produce a brilliant transient source in the process. With different orbital periods, eccentricities, and stellar radii, different masses of the bloated primary envelope, and different companion masses (not to mention the possibility of *compact* companion stars), one can quickly imagine a wide diversity of ejected mass, energy, and luminosity for the resulting transients. This may provide an attractive explanation for the huge diversity in LBV-like eruptions and related transients observed so far (see Smith et al. 2010b), but real models of such an encounter are needed.

5 ORBITAL EVOLUTION

Lastly, we briefly mention one more consequence of the type of stellar collision described above. If these events induce significant ejections of mass from the system — and if the mass ejection is concentrated at periastron — then multiple such encounters could drive rapid orbital evolution. Steady mass loss (as in normal stellar winds) will tend to circularize and widen an orbit over time, but mass loss events concentrated at periastron in an eccentric system will tend to make the system more eccentric.

One can see that initially grazing encounters could potentially escalate quickly to catastrophic collisions. In a mildly eccentric system with a periastron separation not

much larger than the primary star's radius, tidal friction and deposition of energy into the primary star's envelope may be small at first (e.g., Moreno et al. 1997). However, it may initiate a feedback loop where successive encounters disturb and inflate the primary star's envelope, making each subsequent encounter more severe until a true collision is unavoidable. This provides an attractive explanation for the building instability in the few years before a giant LBV eruption, as seen in η Car, SN 1954J, SN 2009ip, UGC 2773-OT, and perhaps HD 5980 (see Smith et al. 2010b).

If these sorts of periastron collisions induce enough mass loss from the system to completely remove the massive primary star's H envelope and thereby form a Wolf-Rayet (WR) star, it would profoundly change the orbit. In particular, each successive periastron mass ejection would leave the system less bound and more eccentric. This type of scenario may therefore provide a reasonable explanation for the origin of very eccentric WR+OB colliding-wind binary systems like WR 140, which has $e=0.88$ (Marchenko et al. 2003). If the periastron mass loss is severe enough, in some cases it may even unbind the system altogether, forming an apparently single WR star. The η Car system will likely be left unbound if it encounters one more mass-loss event as extreme as the 1840s Great Eruption, providing that this mass loss occurs at periastron.

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